AFRL-RX-WP-TP-2009-4149

NUMERICAL SIMULATION OF WEAR IN A C/C COMPOSITE MULTIDISK CLUTCH (PREPRINT)

Shuangmei Zhao, Gregory E. Hilmas, and Lokeswarappa R. Dharani

University of Missouri Rolla

APRIL 2009

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
April 2009	Journal Article Preprint	01 April 2009 – 01 April 2009

4. TITLE AND SUBTITLE	
NUMERICAL SIMULATIONOF WEAR IN A C/C COMPOSITE MULTIDISK CLUTCH (PREPRINT)	5a. CONTRACT NUMBER FA8650-04-C-5704
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 78011F
6. AUTHOR(S)	5d. PROJECT NUMBER 2865
Shuangmei Zhao (Paul Mueller Company) Gregory E. Hilmas and Lokeswarappa R. Dharani (University of Missouri Rolla)	5e. TASK NUMBER 25
	5f. WORK UNIT NUMBER 25100000
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Missouri Rolla 1870 Miner Circle Rolla, MO 65409-0970 Paul Mueller Company 1600 W. Phelps Springfield, MO 65801-0828	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Materials and Manufacturing Directorate Wright-Patterson Air Force Base, OH 45433-7750 Air Force Materiel Command United States Air Force	10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/RXLMP
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RX-WP-TP-2009-4149

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
To be submitted to Carbon
PAO Case Number and clearance date: 88ABW-2009-1172, 25 March 2009.
This work was funded in whole or in part by Department of the Air Force contract FA8650-04-C-5704. The U.S. Government has for itself and others acting on its behalf an unlimited, paid-up, nonexclusive, irrevocable worldwide license to use, modify, reproduce, release, perform, display, or disclose the work by or on behalf of the U.S. Government.

14. ABSTRACT
Friction and wear of engineering components are critical factors influencing the product life. In this study a wear simulation method is presented to investigate the wear behavior of a C/C composite multidisk clutch under simulated operation conditions. A modified Archard's wear model is implemented into a user subroutine which works in association with an axisymmetric finite element model to predict the progress of wear on friction surfaces. An element removal technique is introduced into the finite element analysis to simulate the material loss during wear. Local wear is computed and integrated over the sliding distance using the Euler integration scheme. The progress of wear and wear rate with time and sliding distance is presented.

15. SUBJECT TERMS
friction, multidisk clutch, Euler integration scheme

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Todd J. Turner
Unclassified	Unclassified	Unclassified	SAR	30	19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Numerical simulation of wear in a C/C composite multidisk clutch

Shuangmei Zhao[1], Gregory E. Hilmas[2] and Lokeswarappa R. Dharani[3*]

[1]*Paul Mueller Company, 1600 W. Phelps, Springfield MO 65801-0828 Rolla, U.S.A.*
[2]*Department of Materials Science & Engineering, Missouri University of Science and Technology, Rolla, MO 65409-0340, U.S.A.*
[3]Department of Mechanical and Aerospace Engineering, *Missouri University of Science and Technology, Rolla, MO 65409-0340, U.S.A.*

Abstract

Friction and wear of engineering components are critical factors influencing the product life. In this study a wear simulation method is presented to investigate the wear behavior of a C/C composite multidisk clutch under simulated operation conditions. A modified Archard's wear model is implemented into a user subroutine which works in association with an axisymmetric finite element model to predict the progress of wear on friction surfaces. An element removal technique is introduced into the finite element analysis to simulate the material loss during wear. Local wear is computed and integrated over the sliding distance using the Euler integration scheme. The progress of wear and wear rate with time and sliding distance is presented.

*Corresponding author. Tel: +1-573-341-6504; Fax: +1-573-341-4607.
E-mail address: dharani@mst.edu (Lokeswarappa R. Dharani)

1. Introduction

Wear of engineering components is a critical factor influencing their service life. Wear is defined as a dynamic process of the progressive damage and material loss from the surface of a component due to its motion relative to the adjacent working components [1]. The phenomenon of wear is difficult to model because of the complex structure of contact surfaces, severe deformation in the contact region, frictional heat generation, presence of contaminants and wear debris and atomic level interactions [2]. Extensive research has been conducted in the development of a wear model that can describe a wide variety of wear phenomena reasonably well. Archard was the first to present a wear model to describe sliding wear [3]. In Archard's wear model, it is assumed that the critical parameters in sliding wear are the stress field in the contact region and the relative sliding distance between the contacting surfaces. Archard's work has been followed by extensive scientific and empirical investigations [4-7]. But no single predictive equation could be found for general and practical use.

The numerical simulation of wear has taken advantage of the rapid development of finite element methods for solving non-linear problems. This includes macroscopic wear modeling using a linear wear law [8], finite element simulation of dry sliding wear using a modified Archard's law [9], use of variable step size in a two-dimensional wear simulation [10], modeling the progress of wear [11-13] and simulation of wear mechanisms on pin-on-disk configuration [14].

Carbon-carbon composites (C/C) exhibit an attractive combination of mechanical, thermal and electrical properties and are being used successfully in the aerospace industry [15]. Applications of C/C includes friction materials such as high performance clutches

and brakes in aircraft because of their low weight, excellent thermal and mechanical properties, chemical inertness and self-lubricating capability [16, 17].

Friction and wear behavior of C/C composites has been studied extensively. These studies include the tribological behavior of different C/C composites under varying parameters [18, 19], the braking (simulated-stop) tribological behavior under different initial surface conditions [20], pin-on-disk sliding experiments [21], and the influence of carbon fiber orientation at the wear face on the wear rates and friction coefficients [22]. Ozcan and Filip [23] investigated the micro-mechanisms of failure and related wear processes of two different C/C composites with varying fiber type and matrix architecture after subscale brake dynamometer tests. The friction and wear performance of the C/C composites were studied at different simulated normal landing energy (NLE) and relative humidity (RH) conditions [24].

To date, limited work has been performed to simulate the tribological behavior of aircraft C/C composite clutch systems. A more comprehensive understanding of the tribological behavior of a composite multidisk clutch in the transient regime is necessary in designing the clutch plate in the extreme clutch environments found in today’s aerospace systems. In this study, the progress of wear in a C/C composite multidisk clutch during short-term engagement is simulated using a new finite element wear simulation methodology. Re-meshing and element removal techniques are introduced into the finite element model to update the surface geometry, and therefore provide a realistic contact pressure distribution after the loss of material.

2. Wear model and FE wear simulation procedure

The main task of the finite element analysis in the wear simulation process is to compute the contact pressure fields and therefore calculate the progressive wear depth using a modified Archard's wear law.

2.1. Wear model

The well-established Archard's wear law [3] postulates that the wear rate w (height loss per unit time, m/s) is proportional to the product of the applied pressure P and the sliding velocity V. In order to calculate the change in topography, Archard's wear equation is rewritten in term of the wear depth h at a certain point as a function of the sliding distance S at that point as $\Delta h = kPV\Delta t$. In the finite element analysis, this wear equation is discretized with respect to time as $\Delta h = kPV\Delta t$, where Δh is the height variation and $V\Delta t$ is the sliding distance traveled at that point during time increment Δt. The incremental wear depth is proportional to the wear coefficient, the local contact pressure and the local increment of sliding distance. A good method for estimating local wear coefficient is currently not available. The best available alternative is to measure an average value across the entire contact region. Therefore, it is assumed that the wear coefficient at every point on the contact surfaces is the same.

2.2. Wear modeling procedure

The finite element wear simulation process is performed in the form of a closed loop. It begins with a general finite element (FE) contact simulation that involves modeling of the contact geometry, supplying material properties and applying the boundary conditions. By reading the FE results from the contact simulation, the status of each node

on the contact surfaces (closed or open) is obtained and the contact pressure at each surface node is determined. The wear model described earlier is implemented into the user subroutine FRIC, in the commercial finite element software (ABAQUS, 6.5-1, Pawtucket, RI) [25], to calculate the local wear depth increment (decrease in disk thickness). The total nodal wear depth is the sum of the nodal wear increments. The Euler integration scheme is used to integrate the wear law over the sliding distance.

The local wear depths are different at every surface node, which means that the shape of the contact surface changes continuously with time. However, for the subsequent iteration, the contact surface assumed to be flat with the applied pressure and the progress of wear. The wear depth of the contact surface for each step is the average of the local wear depths at every surface node.

In order to simulate the material loss during the wear process, an element removal technique is introduced into the finite element model to update the surface geometry, and therefore provide a realistic contact pressure distribution after the loss of material. The surface layer of elements on each contact surface is re-meshed in such a way that the new element height equals to wear depth calculated at this wear step. The surface layer elements of each contact surface, corresponding to the amount of material lost at this wear step, are removed from the finite element model. No further element calculations are performed for elements being removed, hence reducing the total computation time. The removed elements remain inactive in subsequent steps. New surface-to-surface contact needs to be established for the new geometry of the model. The modified FE model is then used for the next wear step as the process is repeated. The wear simulation process stops when the rotational speed reaches zero at the end of the engagement.

3. Multidisk clutch model

The aircraft multidisk clutch is dry and similar in configuration to an aircraft brake as shown in figure 1. It consists of multiple rotating disks sandwiched between stationary disks. An axial force is applied to the disks by a hydraulic actuating system. The wheel drives the rotating disks, while torque tube keys restrain stationary disks. The clutch plates are required to resist sliding wear, withstand high peak temperatures and have a stable friction coefficient for different energy stops while minimizing vibration during normal operation. For long service life, the clutch plates should exhibit high thermal capacity and thermal conductivity to dissipate the large amount of frictional heat generated during clutch engagement.

3.1. Geometric and material models

The multidisk clutch is idealized as an axisymmetric problem (figure 2) without sacrificing the accuracy of the results. This results in significant reduction in computing time and storage space. The hydraulic pressure P_h is uniformly distributed on the surface of the pressure plate. The displacement in the z direction on the bottom surface of the back plate is constrained in the design. Heat convection boundary conditions are imposed on all boundaries to account for the heat dissipated to the ambient environment by convection. Heat flux q across the surface due to convection, is given by $q = h(T - T_0)$, where h is heat convection coefficient, T is the surface temperature, and T_0 is the ambient temperature. The inner and outer radii of each clutch plate are 85.7 mm and 168.3 mm, respectively and each plate has a thickness of 26 mm. There are four friction surfaces labeled as fs1, fs2, fs3 and fs4 in figure 2. The mechanical properties of transversely isotropic C/C composite were obtained from the open literature [26].

Power-shift clutches used in aircraft operate for a short period of time with varying sliding speed. The fast deceleration required for an aircraft takeoff or landing generates a tremendous amount of frictional heat [27] and the surface temperature of the friction disks can reach as high as 2000^{o}C [26]. Therefore, temperature-dependent thermal properties [27] are used. Since it has been found that the sliding speed decreases linearly with time during the braking process [20], the angular speed of the rotating disks is assumed to vary linearly with time during engagement.

3.2. Finite element model

A 2D axisymmetric finite element model (figure 3) is developed to investigate wear of a C/C composite clutch under simulated operating conditions using the commercial finite element software ABAQUS [25]. Since the temperature gradient is localized near the friction surfaces, and the loss of material occurs at the contact surfaces, a finer mesh is applied on the contact surfaces. Because the contact problems are nonlinear, in order to obtain accurate solutions, iterative schemes are used.

Surface-to-surface contact pairs are set up between the friction surfaces. Surface interaction in coupled thermal-mechanical contact simulations includes heat exchange by conduction and radiation as well as the generation of frictional heat in coupled simulations. At each pair of nodes at the interface, the normal displacements must be continuous (no penetration) and the equilibrium condition (equal and opposite tractions) must be satisfied. Additionally, at each pair of nodes on the frictional surfaces the temperature continuity and the heat balance conditions must be satisfied.

The subroutine FRIC in ABAQUS code [25] is called only when the contact point is closed. In the subroutine, the heat generated by friction in each time increment at each

point on the friction surfaces is calculated as $\Delta q = \mu r \omega P \Delta t$, where Δt is the time increment, Δq is the heat flux increment, μ is the friction coefficient, r is the radius of that point, ω is the rotational speed at time t and P is the local contact pressure.

4. Results and discussions

In order to validate the wear model, the FE wear simulation method described above is used to simulate disk-on-disk sliding wear tests. The FEA results are then compared with the wear test results obtained from the open literature [20].

4.1. Validation of FE wear simulation model

Lee *et al*. [20] conducted friction and wear tests in air using a homemade disk-on-disk sliding wear tester. Rotor-shaped specimens having an inner radius, outer radius and thickness of 5 mm, 12.5 mm and 5 mm, respectively, were tested under simulated stop (braking) tests. The tests were performed by first accelerating the rotor specimen to the desired speed (1400 or 2000 rpm) and second, shutting off the power. At the same time, the stator specimen was loaded with a pressure of 1.7 MPa to slide against the rotor until both the stator and rotor stopped completely. The test results showed that the braking times were 26 s for a speed of 1400 rpm and 40 s for a speed of 2000 rpm.

A finite element model is developed to simulate the wear behavior of C/C composite under the simulated-stop test condition by employing the wear simulation method described earlier. The time-dependent friction coefficient (figure 4) is evaluated from the test results in Figs. 5 and 6 of Lee et al. [20]. It is then implemented into the finite element model to better simulate the friction and wear test.

The wear coefficient can be calculated using the following equation [8, 21] $k = v/(F_n S)$, where v is the wear volume, F_n is the applied normal load and S is the sliding distance. The sliding distances of the simulated-stop tests are calculated as 16.676 m (1400 rpm) and 36.645 m (2000 rpm) according to the experiment data [20]. From the test results shown in Fig. 10 of Lee et al. [20], the weight losses were read as 1 mg (1400 rpm) and 2 mg (2000 rpm). Using the above equation, the wear coefficients are evaluated for sliding speeds of 1400 rpm and 2000 rpm to be 4.73×10^{-14} Pa^{-1} and 4.30×10^{-14} Pa^{-1}, respectively.

Additional material properties (temperature-dependent specific heat and thermal conductivity) of C/C composites needed for this numerical analysis were obtained from published literature [26, 27]. According to the FEA results, the wear depths after the braking tests are 1.320 μm (26 s) and 2.643 μm (40 s), which correspond to weight losses of 0.985 mg and 1.972 mg. The FEA results are almost same as that of the braking test results (1 mg and 2 mg, respectively). Therefore, the finite element wear simulation method developed in this study is capable of predicting the amount of wear reasonably well.

4.2. Wear simulation results of multidisk clutch

Power-shift clutches used in aircraft operate for a very short period of time with the sliding speed decreasing from an initially high value to zero within a few seconds [28]. The simulated engagement time is taken to be 4 seconds. The actual value of wear coefficient k for a particular contact pair should be experimentally determined. For the multidisk clutch under consideration, the simulated operating conditions are chosen to be 1.7 MPa and 2000 rpm. The wear coefficient of $k = 4.30 \times 10^{-14}$ Pa^{-1}, calculated from the

experimental data in the previous section, is used in the multidisk clutch study. The following material properties and operating conditions are used in obtaining the results: density ρ = 1810 kg/m^3, elastic moduli E_r = 50.2 GPa, E_z = 5.89 GPa, shear modulus G_{rz} = 2.46 GPa, Poisson's ratios $\nu_{r\theta}$ = 0.30, ν_{rz} = 0.33, thermal expansion coefficients α_r = 0.31x10^{-6}/K, α_z = 0.29x10^{-6}/K, friction coefficient $\mu = 0.20$, heat convection coefficient h = 100 W/m^{2}K, wear coefficient k = 4.3x10^{-14} Pa^{-1}, hydraulic pressure P = 1.7 MPa, initial rotational speed ω = 2000 rpm, engagement time s = 4 sec. In addition, the temperature-dependent specific heat and thermal conductivity data cited earlier [26, 27] are also used.

Figure 5 shows the wear at each node along a typical friction surface. The wear is clearly non-uniform along a given friction surface. The average of these nodal wear values is calculated and used in the element removal technique for future calculation. The average wear value at the end of 1 sec is around 1.7 μm.

The progress of wear with time is presented in figure 6. At the end of the engagement cycle, the wear depth of each friction surface reaches 3.815 μm, which is 0.015% of the original disk thickness (26 mm). The slope of the curve is decreasing steadily because the sliding velocity decreases continuously with time. The decrease in sliding velocity results in a lower frictional heat and a decrease in the sliding distance over the same time increment during engagement. The wear rate (height loss per unit time) versus time that can be obtained from figure 6 shows that it decreases linearly with time from 1.9 μm/s to 0 during the engagement cycle.

The corresponding contact pressure distribution on the friction surface at 4 s into the engagement cycle is presented in figure 7. Although the applied uniform pressure is 1.7 MPa, the contact pressure is approximately 1.9 ~ 2.1 MPa everywhere except for at the

ends. Sudden decreases in contact pressure are observed at the inner and outer radii, which indicate a loss of contact or diminished contact. This phenomenon may be caused by a thermal expansion effect. Generally, the distribution of contact pressure on the friction surface varies because of thermal deformation [29]. Thermal convection at the ends of the clutch disk result in a lower temperature near the inner and outer radii compared to the interior of the friction surface. The higher temperature leads to a larger thermal expansion in the interior portion of the clutch disk, which eventually results in loss of contact at the ends.

The average wear (weight loss) over the sliding distance on friction surface is also calculated using the model. During one simulated engagement cycle, the angular speed linearly decreases from 2000 rpm to zero in 4 seconds. Under the simulated operating conditions, the sliding distance is calculated as 53.2 m for one engagement cycle. The weight loss during the engagement cycle increases almost linearly with the sliding distance from 0 to 450 mg. The parameters involved in the Archard's wear law are the wear coefficient, local contact pressure and sliding distance. Since the wear coefficient is assumed to be a constant in this study, the evolution of wear over the sliding distance is only dependent on the contact pressure. After investigating the evolution of contact pressure, it is found that the contact pressure has only a slight variation during the engagement period. Therefore, wear of the multidisk clutch is linearly related with the sliding distance.

To obtain a better understanding of the weight loss variation with sliding distance, a wear rate based on the weight loss over unit sliding distance is plotted in figure 8. The wear rate remains a constant until a dramatic reduction occurs at the final stage of the

engagement cycle. At the end of the engagement cycle, the increment of weight loss is zero owing to the fact that the clutch disk has reached a complete stop, thus resulting in the zero wear rate.

6. Conclusions

A finite element wear simulation method was developed to investigate the wear behavior of a C/C composite multidisk clutch, consisting of four friction surfaces, under simulated operating conditions. An element removal technique was applied in a finite element analysis to simulate the material loss during wear testing. The wear depth was calculated using a modified Archard's wear law. The FEA results compare favorably with the available experimental data for wear tests of C/C composites found in the literature, validating the wear simulation method developed herein. The wear, and wear rate as functions of time and sliding distance were obtained for a multidisk clutch architecture during simulated engagement cycle.

Acknowledgement

This work is supported by Air Force Research Laboratory through the Center for Aerospace Manufacturing Technologies (CAMT) under Contract No. FA8650-04-C-5704.

References

[1] Gahr KHZ. Microstructure and wear of materials. New York: Elsevier. 1987; 132-5.

[2] Ludema KC. Friction, Wear, Lubrication – A Textbook in Tribology. New York: CRC Press. 1996; 127-30.

[3] Archard JF. Contact and rubbing of flat surfaces. J Appl Phys 1953; 24; 981-8.

[4] Rigney DA. The roles of hardness in the sliding behavior of materials. Wear 1994; 175; 63-9.

[5] Meng HC, Ludema KC. Wear models and predictive equations: their form and content. Wear 1995; 181-3; 443-57.

[6] Hsu SM, Shen MC, Ruff AW. Wear predictions for metals, Tribo Int. 1997; 30 377-83.

[7] Williams JA. Wear modeling: analytical, computational and mapping: a continuum mechanics approach. Wear 1999; 225-9; 1-17.

[8] Podra P, Andersson S. Simulating sliding wear with finite element method. Tribo Int 1999; 32; 71-81.

[9] Molinari JF, Ortiz M, Radovitzky R, E.A. Repetto. Finite element modeling of dry sliding wear in metals, Eng Comput 2001; 18; 592-610.

[10] Oqvist M. Numerical simulations of mild wear using updated geometry with different step size approaches. Wear 2001; 249; 6-11.

[11] Kim NH, Won D, Burris D, Holtkamp B, Gessel, Swanson P, et al. Finite element analysis and experiments of metal/metal wear in oscillatory contacts. Wear 2005; 258; 1787-93.

[12] Gonzalez C, Martin A, Llorca J, Garrido MA, Gomez MT, Rico A, et al. Numerical analysis of pin on disk tests on Al-Li/SiC composites, Wear 2005; 259; 609-612.

[13] Hegadekatte V, Huber N, Kraft O. Finite element based simulation of dry sliding wear, Modelling Simul. Mater Sci Eng 2005; 13; 57-75.

[14] Cantizano A, Carnicero A, Zavarise G. Numerical simulation of wear-mechanism maps, Comput Mater Sci 2002; 25; 54-60.

[15] Windhorst T, Blount G. Carbon-carbon composites: a summary of recent developments and applications, Mater & Des 1997; 18; 11-15.

[16] Blanco C, Bermenjo J, Marsh H, Menendez R. Chemical and physical properties of carbon as related to brake performance, Wear 1997; 213; 1-12.

[17] Sogabe T et al. Effect of boron-doping on structure and some properties of carbon-carbon composites, J. Mater Sci 1996; 30; 6469-76.

[18] Chen JD, Ju CP. Friction and wear of PAN/pitch-, Pan/CVI- and pitch/resin/CVI-based carbon/carbon composites. Wear 1994; 174; 129-35.

[19] Chen JD, Chern Lin JH, Ju CP, Effect of load on tribological behavior of carbon-carbon composites, J Mater Sci 1996; 31; 1221-9.

[20] Lee KJ, Chern Lin JH, and Ju CP. Surface effect on braking behavior of PAN-pitch carbon-carbon composite. Wear 1996; 199; 228-36.

[21] Gomes JR, Silva OM, Silva CM, Pardini LC, Silva RF. The effect of sliding speed and temperature on the tribological behavior of carbon-carbon composites. Wear 2001; 249; 240-5.

[22] Hutton TJ, Johnson D, McEnaney B. Effects of fiber orientation on the tribology of a model carbon-carbon composite. Wear 2001; 249; 647-55.

[23] Ozcan S, Filip P. Microstructure and wear mechanisms in C/C composites. Wear 2005; 259; 642-50.

[24] Krkoska M, Filip P. Humidity and frictional performance of C/C composites. In: M. Brito, P. Filip, C. Lewinsohn, A. Sayir, M. Opeka and W.M. Mullins, Eds, Development in Advanced Ceramic and Composites. Ceramic Engineering and Science Proceedings. 2005; Vol 26, Cincinnati; The American Ceramic Society. 139-155.

[25] ABAQUS, Version 6.5, ABAQUS, Inc. 2005.

[26] Choi J, Han J, Lee I. Transient analysis of thermoelastic contact behaviors in composite multidisk brakes. J Thermal Stresses 2004; 27; 1149-67.

[27] Marx DT, Polocandriotes T, Zhang S, Scott J, Dinwiddie RB, Wang H. Measurement of interfacial temperatures during testing of a subscale aircraft brake. J Phys D: Appl. Phys 2001; 34; 976-84.

[28] Zagrodzki P, Truncone S. Generation of hot spots in a wet multidisk clutch during short-term engagement. Wear 2003; 254; 474-91.

[29] Burton R. Thermal deformation in frictionally heated contact. Wear 1980; 59; 1-20.

List of Figures:

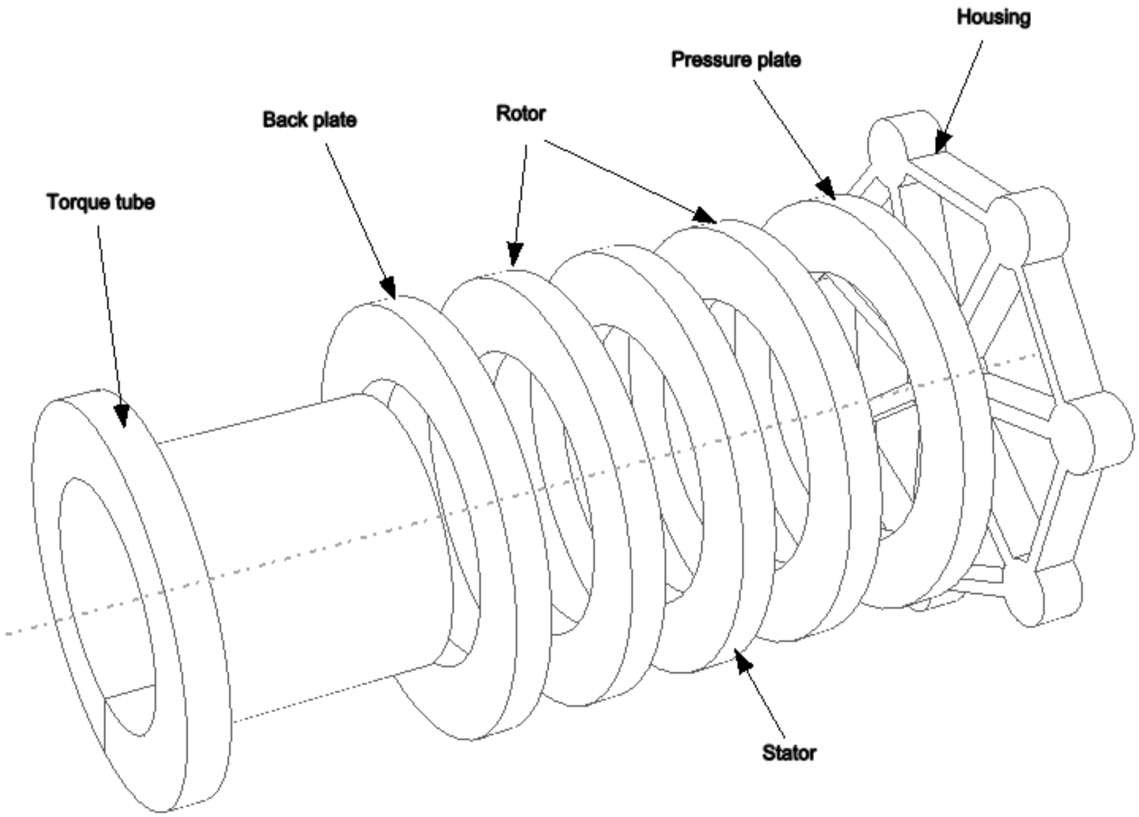


Figure 1. Illustration of a C/C aircraft multidisk clutch.

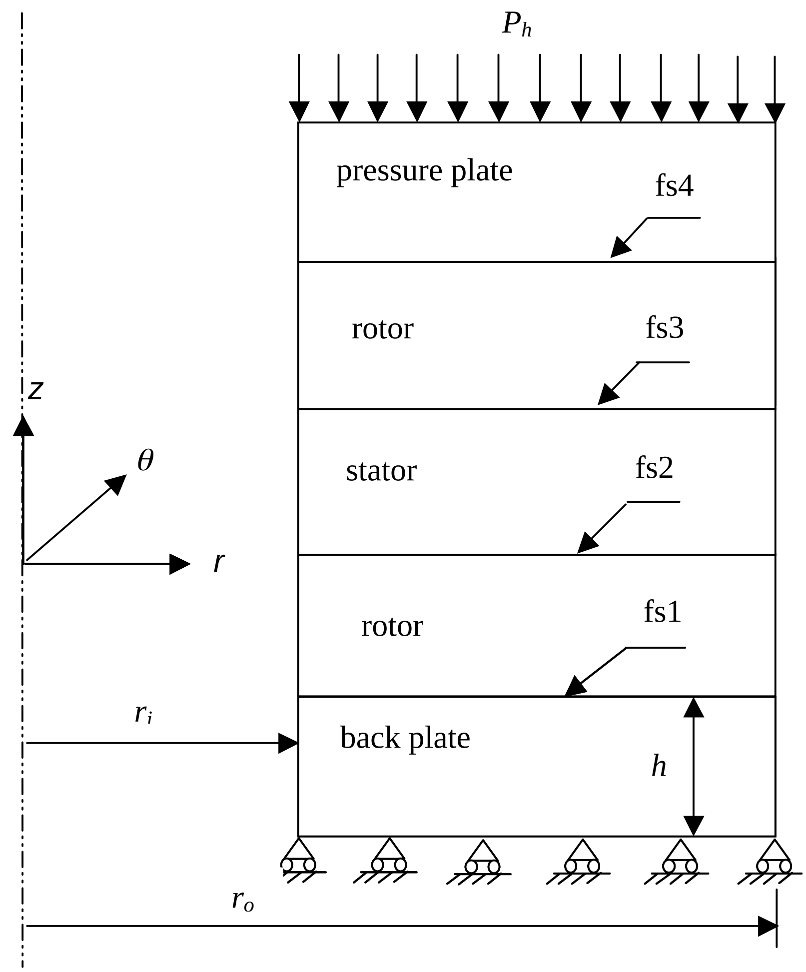
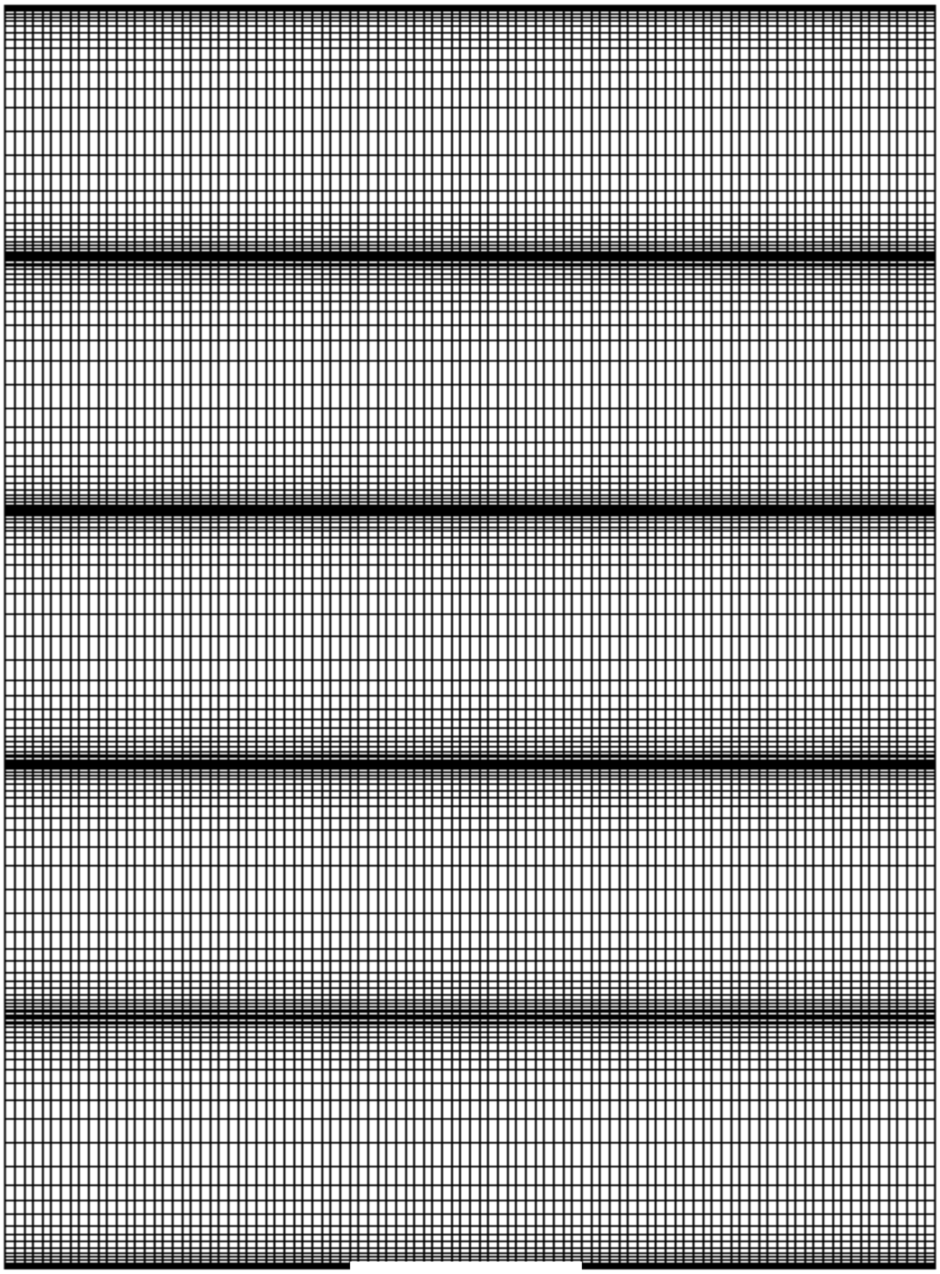


Figure 2. Schematic of the idealized axisymmetric model for aircraft multidisk clutch.

$q = h\,(T - T_0)$



$q = h\,(T - T_0)$

Figure 3. Finite element mesh of the multidisk clutch.

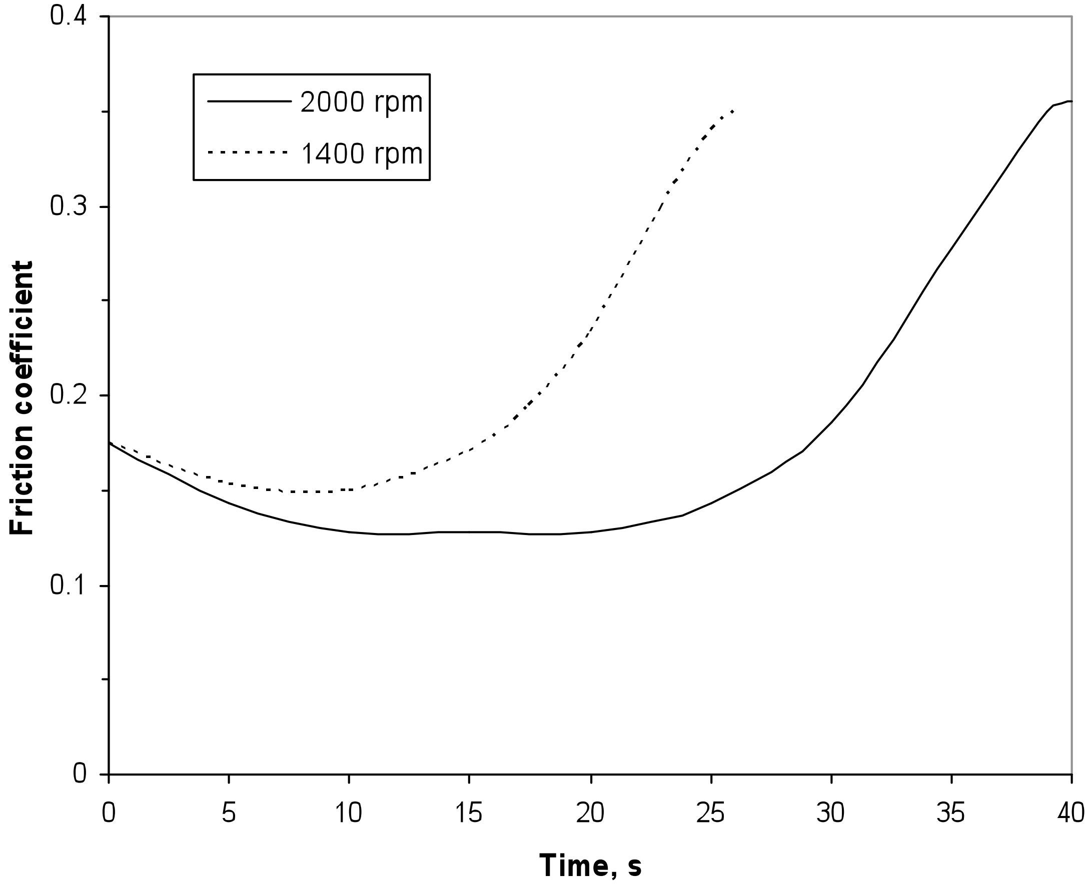


Figure 4. Variation of friction coefficient with time.

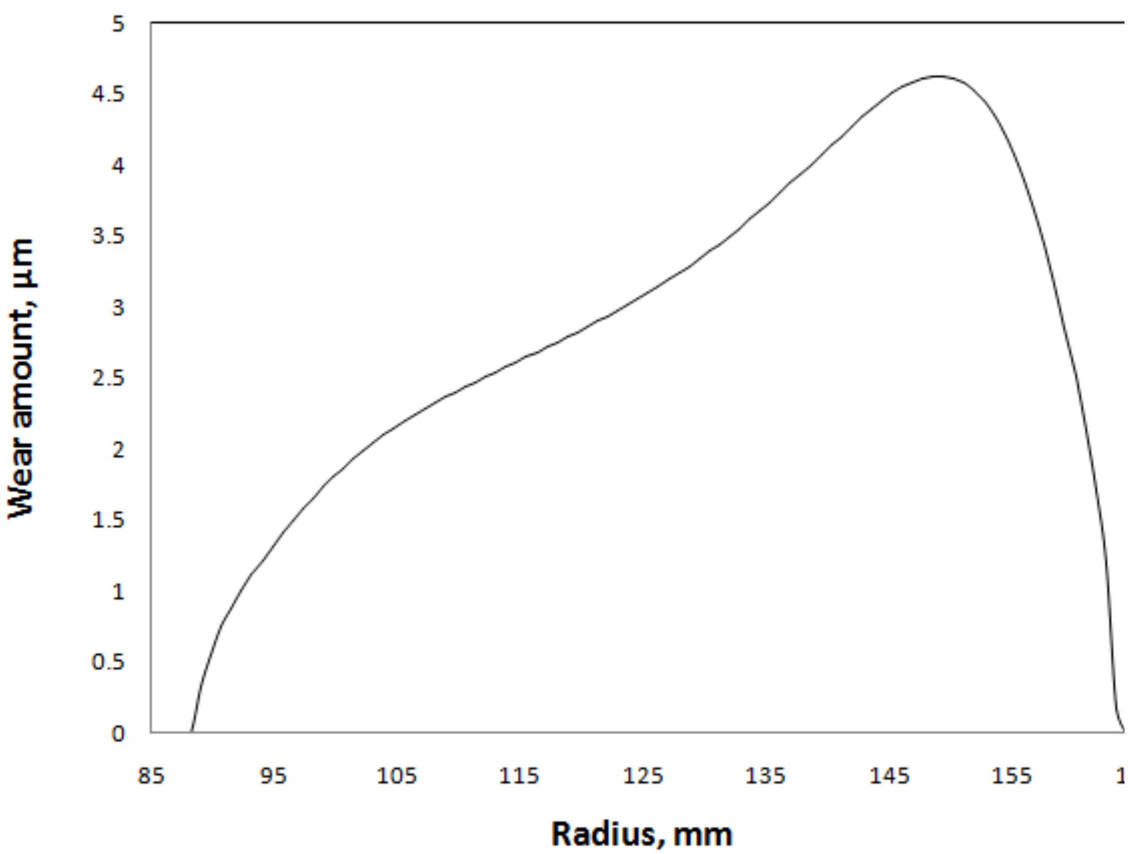


Figure 5. Wear at each node along the friction surface

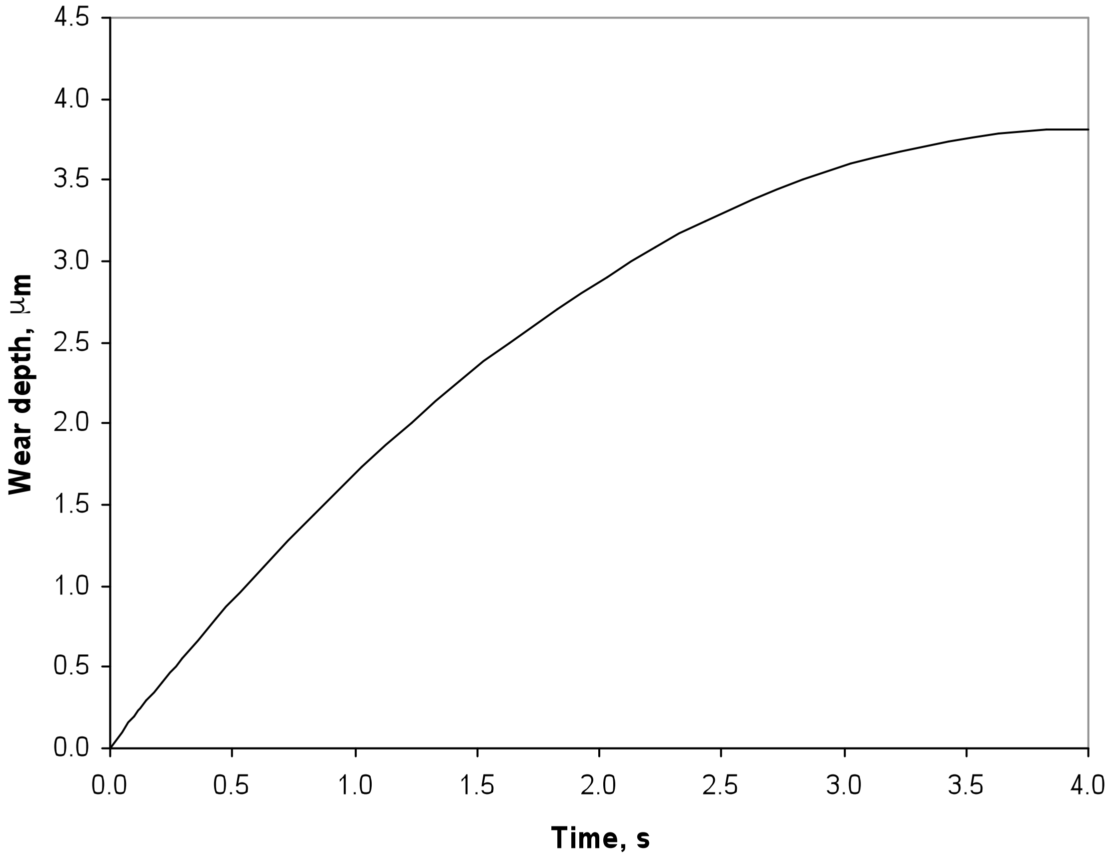


Figure 6. Progress of wear with time.

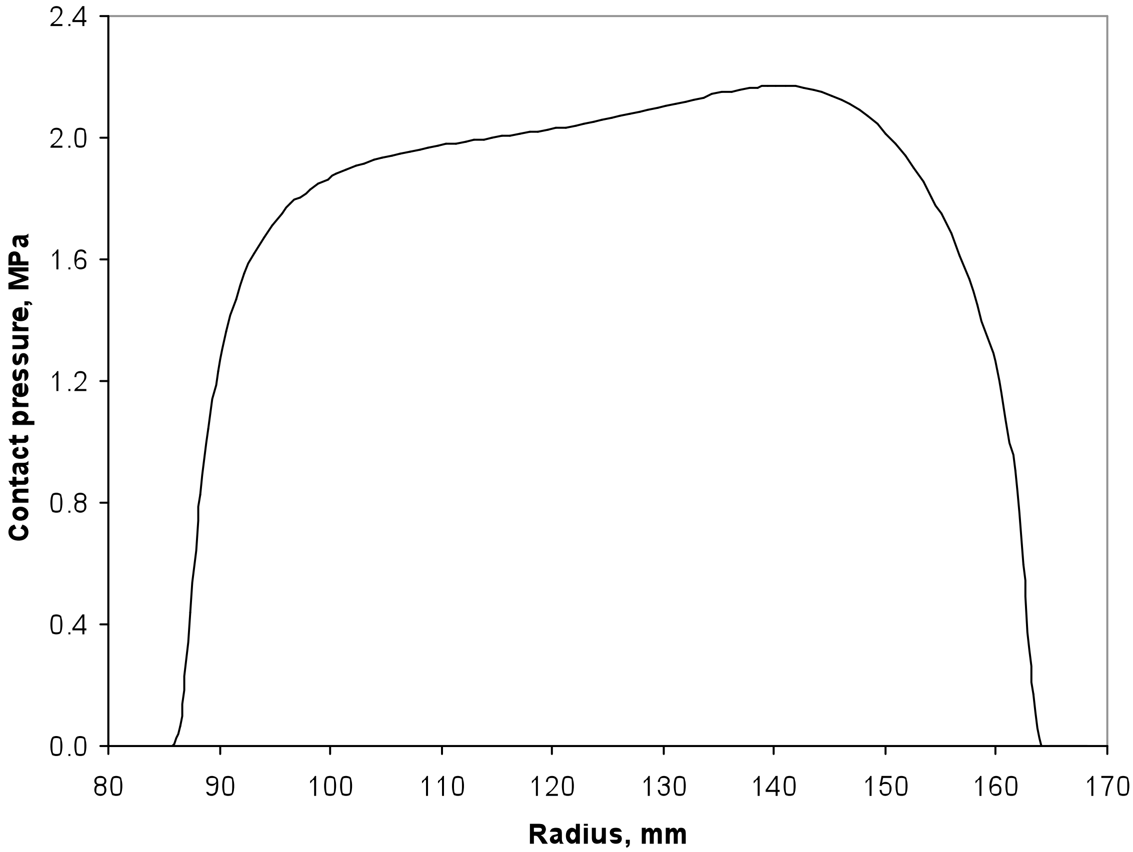


Figure 7. Contact pressure distribution on friction surface at t = 4 s.

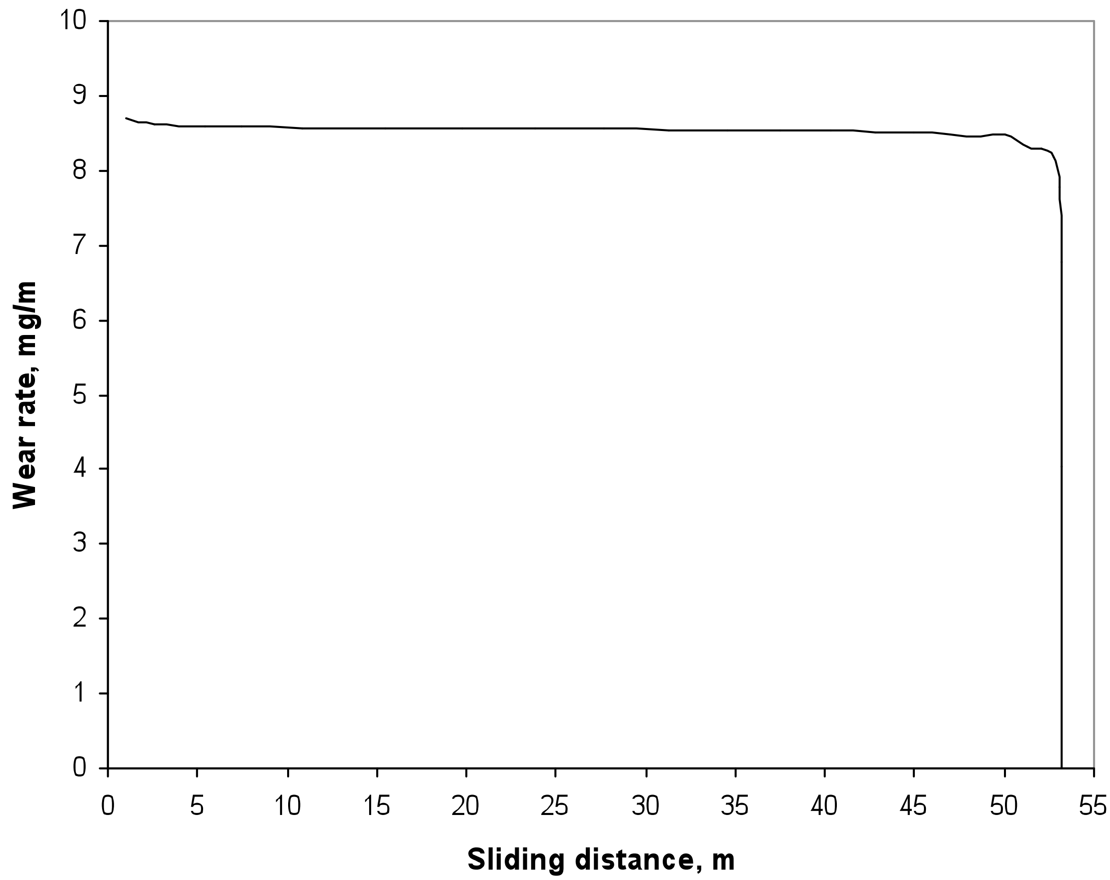


Figure 8. Wear rate (weight loss per sliding distance) variation with sliding distance.